Measurement of Top Quark Properties At CDF

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For the CDF Collaboration

top2008

International Workshop on Top Quark Physics

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We heard about

- ttbar cross section
- Top quark mass
- Single top production
- Tools for top
- Top as tool

Let's talk about

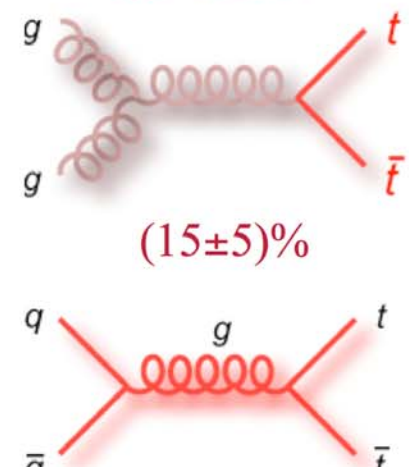
- Top as a laboratory
  - $\sigma(gg \rightarrow ttbar)/\sigma(ppbar \rightarrow ttbar)$
  - Width/lifetime
  - $d\sigma/dM_{ttbar}$
  - Top Charge
  - AFB
  - W helicity
  - $BR(t \rightarrow Wb)/BR(t \rightarrow Wq)$

σ(gg→ttbar)/σ(pp→ttbar)

Motivation

- Test of pQCD calculations
- Gluon Parton Distribution Function (PDF) uncertainty
- Beyond Standard Model (BSM) production and decay mechanisms for top quark

At ~2 TeV



The Challenge

- Discriminate between identical final states

Lepton+jet selection

✓ one and only one high p_T e or μ
✓ missing E_T of at least 20 GeV
✓ ≥ 4 jets with $E_T \geq 15$ GeV, $|\eta| \leq 2$
✓ at least one b-tagged jet

I - Using Low p_T Track Multiplicity…

- Identical Final States ⇒ Difference is in underlying activity
- Gluons are more likely than quarks to radiate low momentum gluons
  - Correlation between number of hard gluons and low p_T tracks
- Large theoretical uncertainties in modeling low p_T gluon radiation
  - Employ a data-driven technique

Subtract g and $qq \rightarrow qq$ contributions from W+0 jet and Dijet 80-100 GeV sample, respectively

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  - s and low p_T tracks
- g low p_T gluon radiation

- Track Multiplicity, N_{trk}
  - Low p_T
  - $|\eta| \leq 1.1$
  - Matched to the event vertex
  - Away from jets
  - Correct for area differences
  - Correct for remaining jet contributions

Subtract g and qq→qq contributions from W+0 jet and Dijet 80-100 GeV sample, respectively

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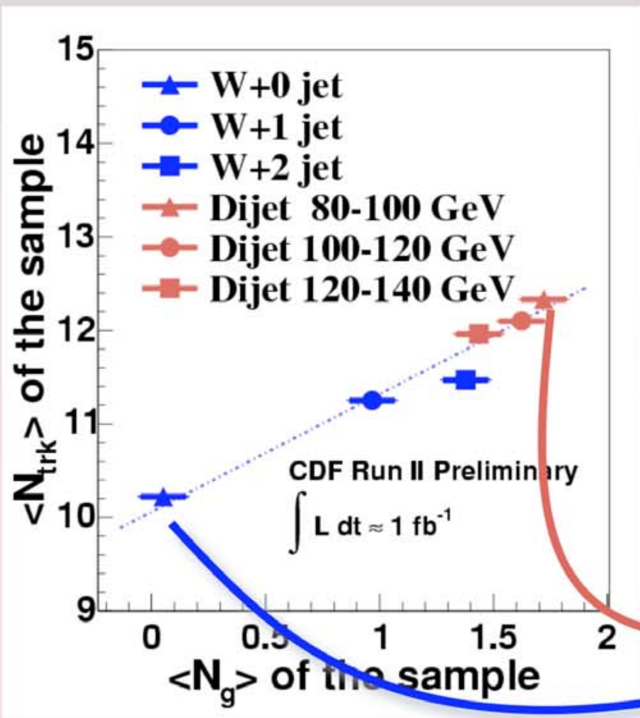
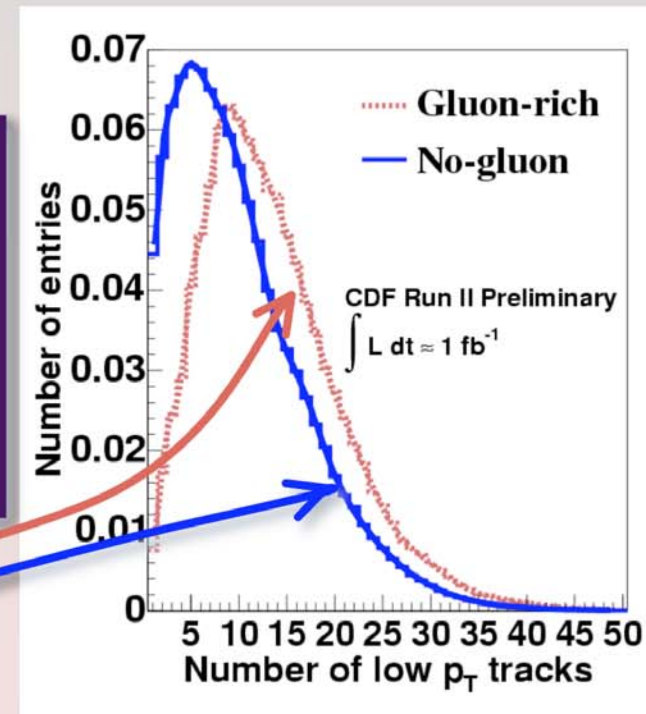


Can define track multiplicity, Ntrk, distribution for a sample with a given average number of hard gluons, <Ng>.



Subtract g and qq→qq contributions from W+0 jet and Dijet 80-100 GeV sample, respectively

…I - Using Low p_T Track Multiplicity…

- Use the normalized parameterization of the two distributions in a fit to the low p_T track multiplicity distribution in any other sample

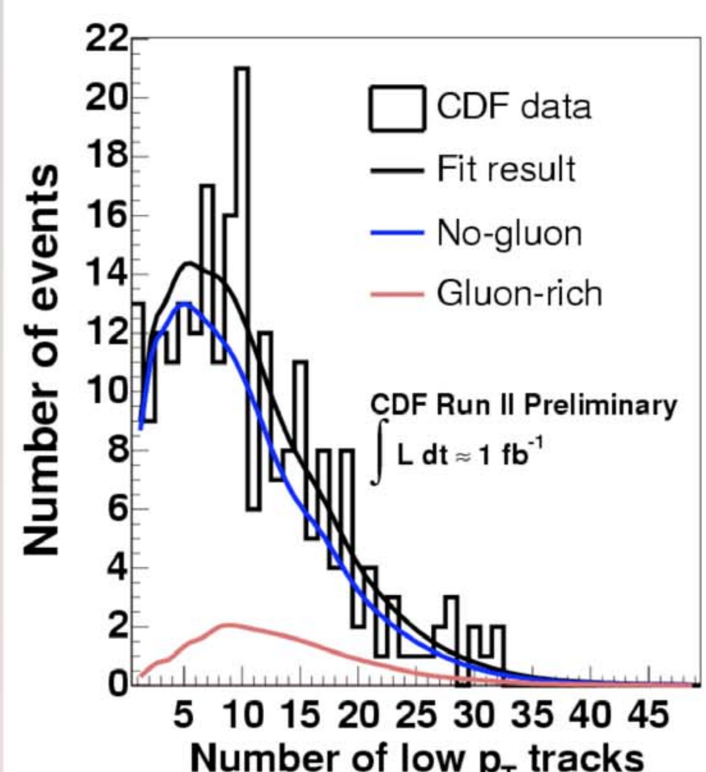
$$N\left[f_g F_g(N_{trk}) + (1 - f_g)F_q(N_{trk})\right]$$

- Has contributions from signal and background
  - Estimating from W+n jet tagged and no-tag samples, and using background fractions from cross section measurements, we find background contribution to the fraction of gluon-rich events to be $f_g^{bkg} = 0.53 \pm 0.11$
- Using acceptances for ttbar events through gg and qqbar production channels, we find

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 0.07 \pm 0.14(stat) \pm 0.07(syst)$$

corresponding to an upper limit of 0.33 @ 95% C.L.

in agreement with pQCD prediction



$$f_g^{W+\geq 4\ jet} = 0.15 \pm 0.14(stat)$$

...I - Using Low p_T Track Multiplicity

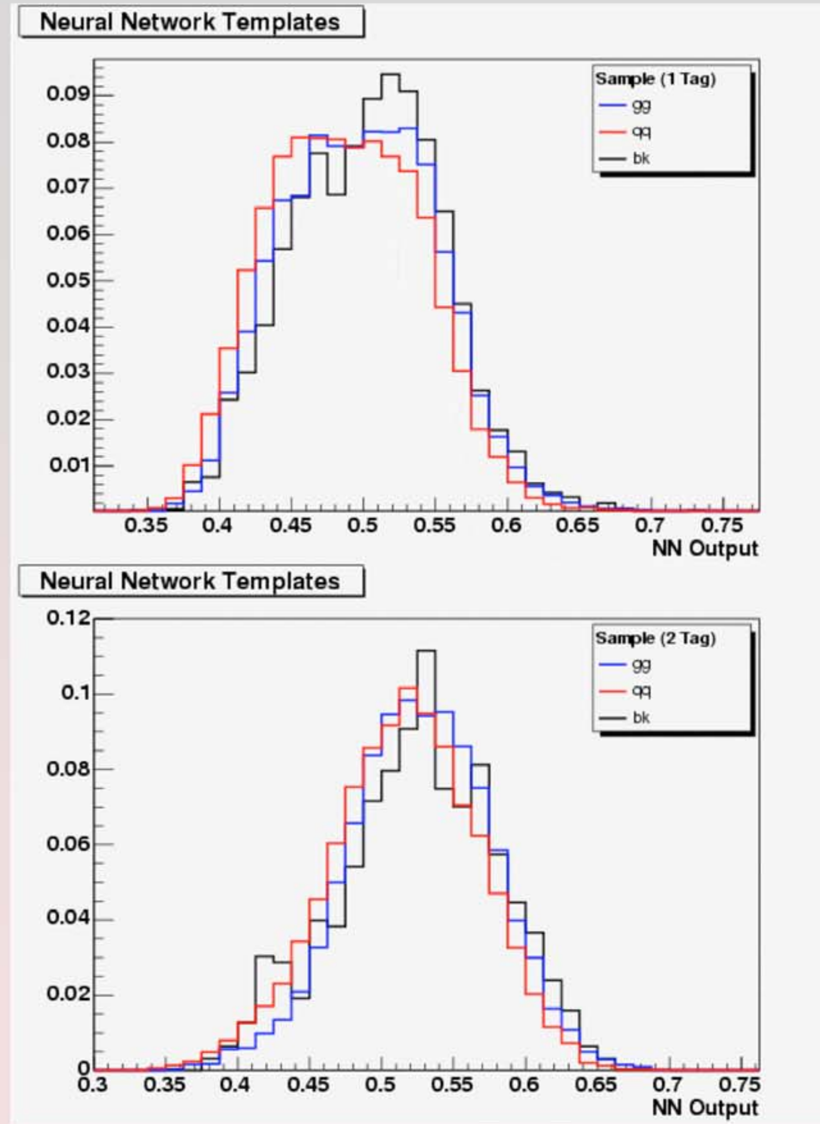
Sources of Systematic Uncertainties (SSU)	f_g	f_g^{bkg}
Track/jet correction	±0.051	±0.001
Low jet E_T cut	±0.021	±0.035
Dijet $qq \rightarrow qq$ fraction	±0.002	±0.019
W+0 jet f_g	±0.039	±0.007
nonW background composition	-	±0.057
f_g^{bkg} calculation	-	±0.089
Total	±0.07	±0.11

SSU	f_g^{tt}
f_g	±0.08
f_g^{bkg}	±0.02
f_b	±0.01
Total	±0.08

SSU	$\sigma(gg \rightarrow tt)/\sigma(pp \rightarrow tt)$
f_g^{tt}	±0.07
$\mathcal{A}_{gg \rightarrow tt}/\mathcal{A}_{qq \rightarrow tt}$	±0.004
Total	±0.07

II - Using Multivariate Neural Network (NN)…

- Identical Final States ⇒ The difference lies in the kinematic properties
- 8 kinematic variables are used
  - 2 related to the production
  - 6 from decay products preserving spin information of top quarks
- Same selection criteria, divided based on number of tags
- Assume the same shape for all backgrounds (W+4 jets)
- Define 3 NN output templates
  - gg→ttbar
  - qqbar→ttbar
  - W+ jet

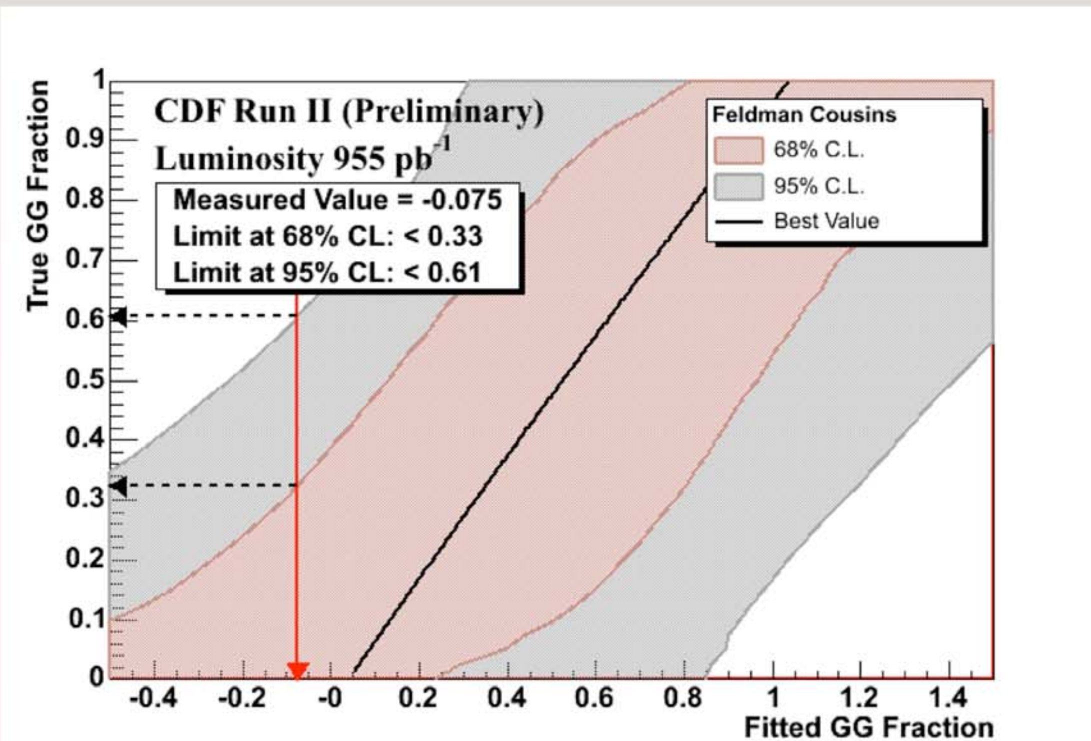


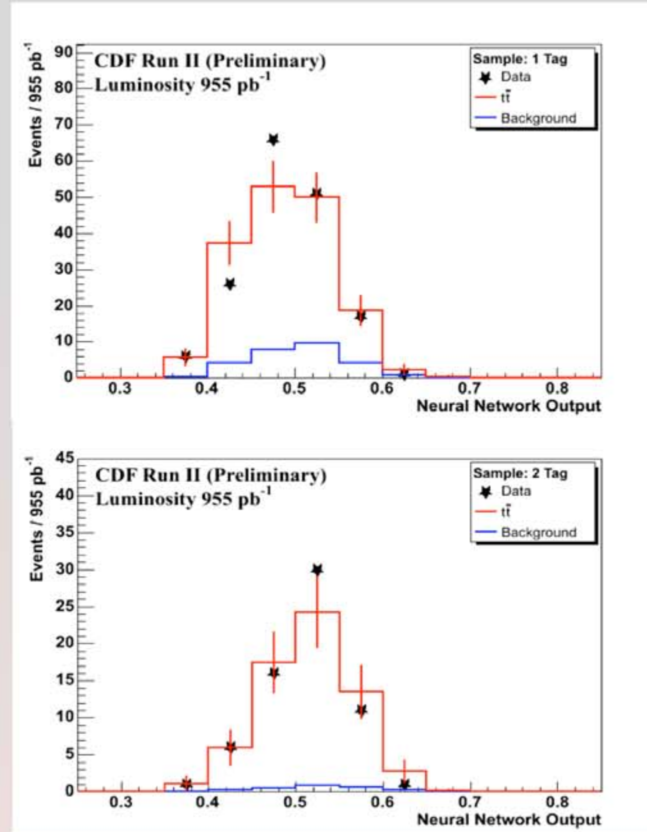
…II - Using Multivariate NN

- Use a maximum likelihood fit

$\mathcal{L}(C_f)=\mathcal{L}^{1T}(C_f,C_s^{1T})\mathcal{L}^{2T}(C_f,C_s^{2T})$

- Define a Feldman-Cousin (FC) confidence band
  - Pseudo-experiments for varying true gg→ttbar fraction, C_f^{true}, within 0 and 1

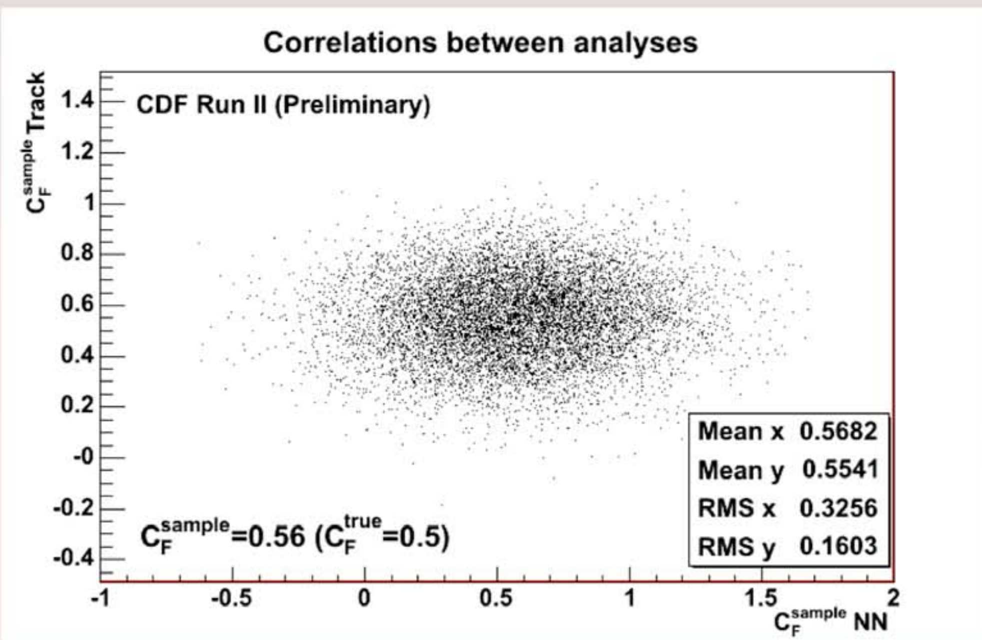




Upper limits on
σ(gg→ttbar)/σ(ppbar→ttbar)
0.33 @ 68% C.L.
0.61 @ 95% C.L.

Combination of Track and NN Analyses

- The gluon-rich and no-gluon low p_T track distributions are used to morph the MC prediction in pseudo-experiments
- Pseudo-experiments are used to define FC confidence band for the track analysis as well



Correlated Systematic Uncertainties

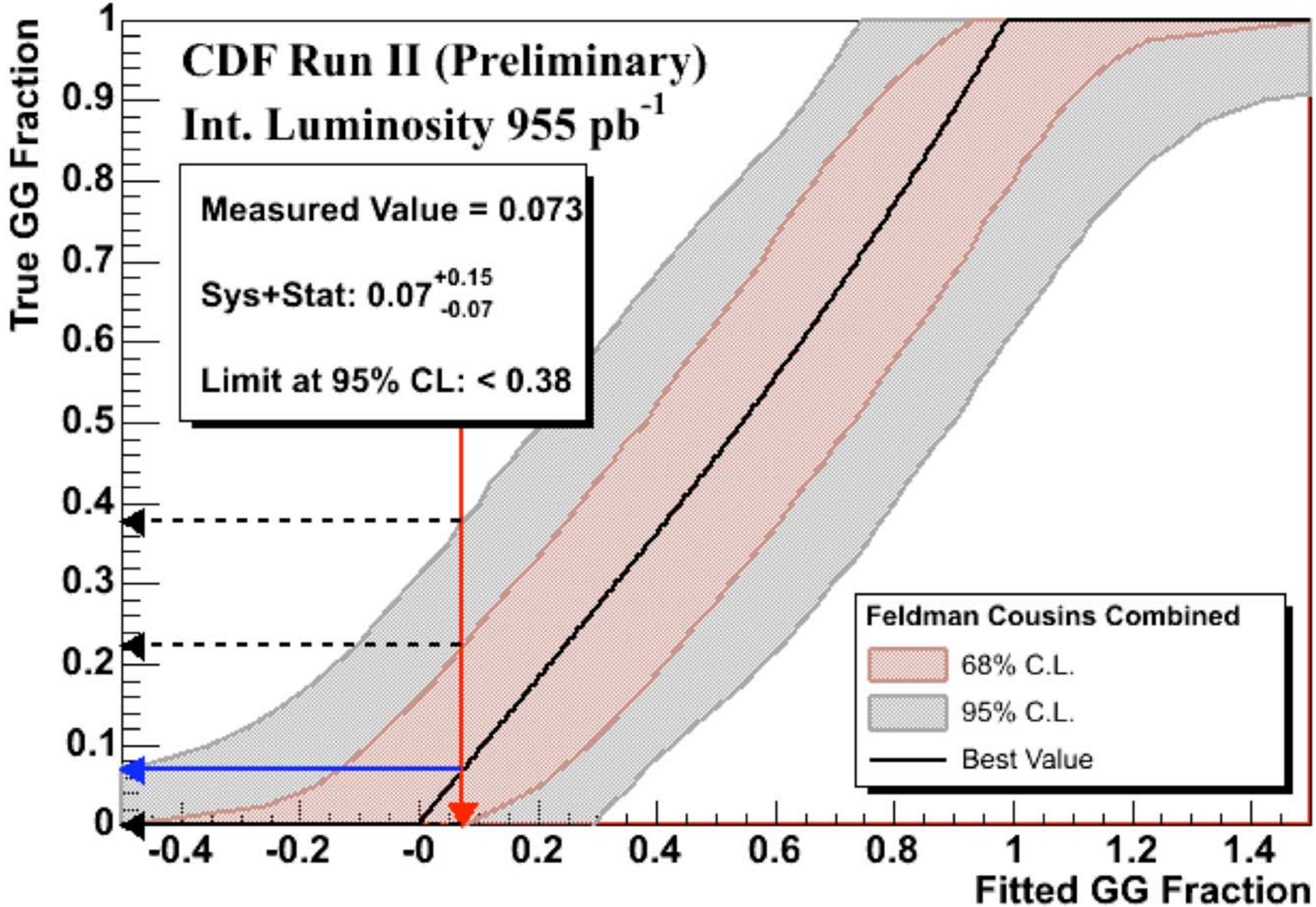
Sources related to the background estimate

Uncorrelated Uncertainties

Statistical uncertainties

All other systematic uncertainties

- For each method we smear the result of PE with a Gaussian distribution associated with the uncertainties, correlated or not
- Weight each result to construct a value for the combined method



CDF Run II (Preliminary)
Int. Luminosity 955 pb^{-1}
Measured Value = 0.073
Sys+Stat: $0.07^{+0.15}_{-0.07}$
Limit at 95% CL: < 0.38
Feldman Cousins Combined
68% C.L.
95% C.L.
Best Value
True GG Fraction
Fitted GG Fraction

$d\sigma/dM_{ttbar}$…

Motivation

Test of the SM prediction

Hint to BSM physics

Definition

$$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{A_i \int L \Delta^i_{M_{t\bar{t}}}}$$

N_i = number of events in bin i

N_i^{bkg} = number of predicted background events in bin i

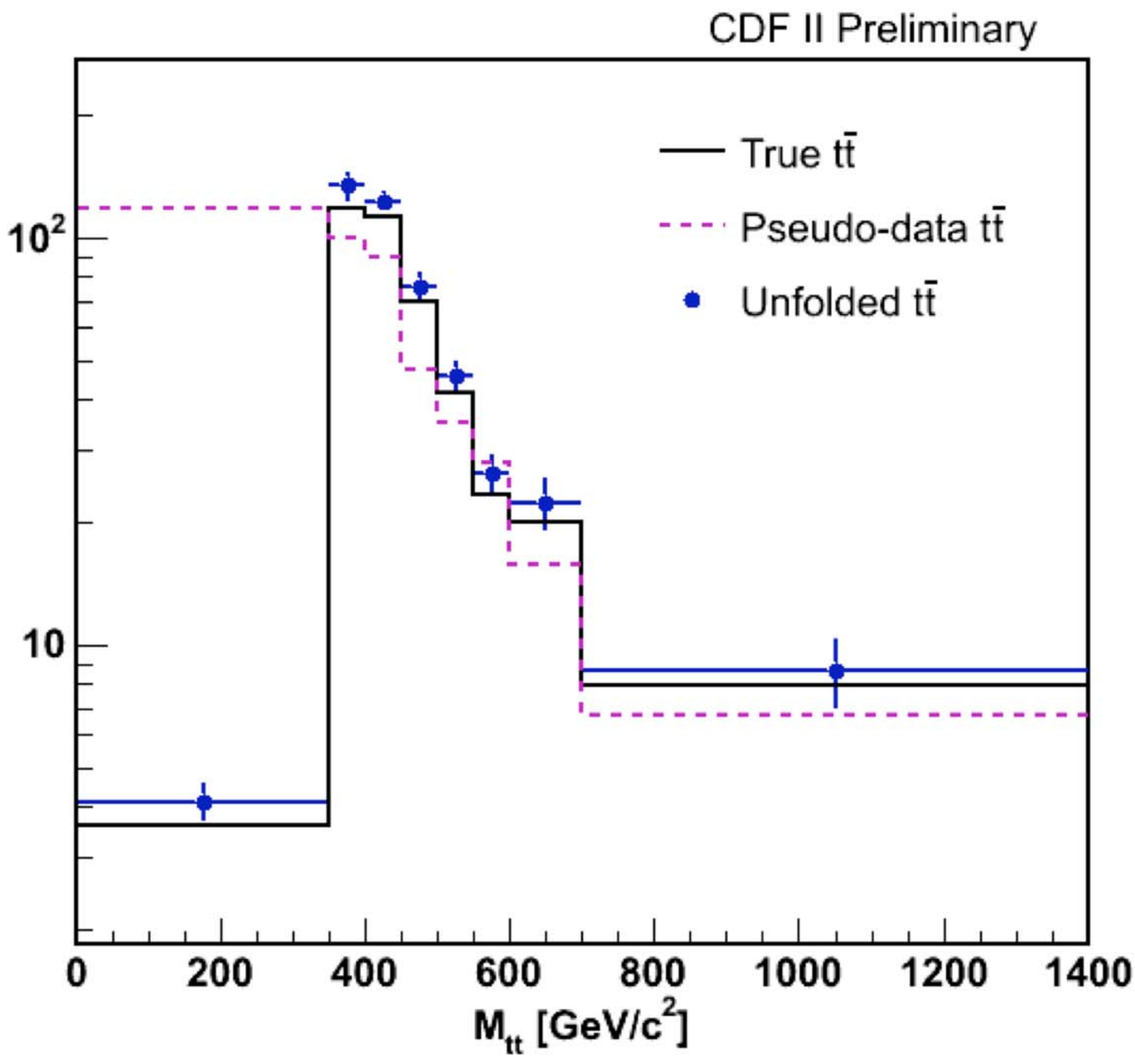
A_i = acceptance in bin i

Δ^i_{Mttbar} = the width of bin i

$\int L$ = integrated luminosity

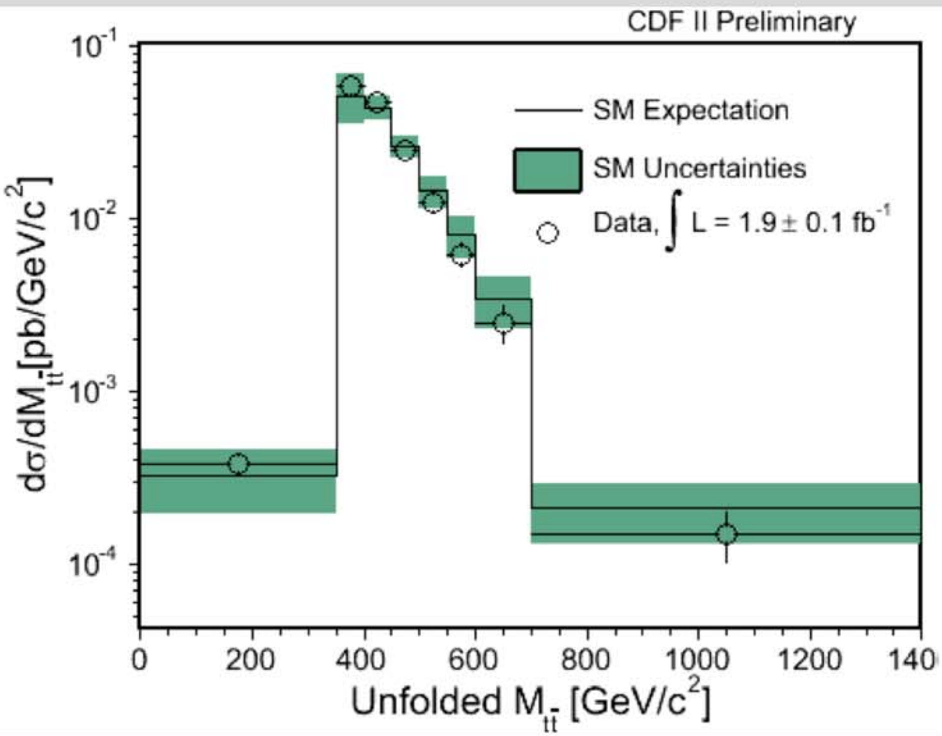
Use 8 bins, all except the first and last bins have equal width

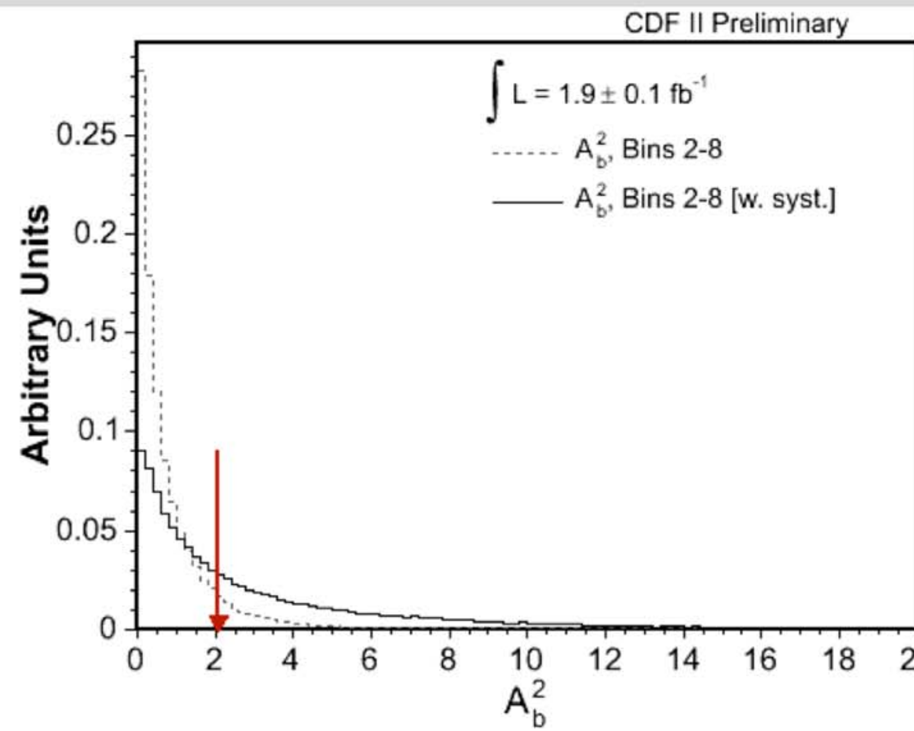
- Same “lepton+jets” selection
- Using the four vectors of the 4 leading jets, lepton and the missing E_T measure the Mttbar in each event
- Correct the reconstructed Mttbar distribution for the distortion due to
  - Detector effects and
  - Geometric and kinematic acceptance
- Use a regularized unfolding technique, Singular Value Decomposition (SVD)


CDF II Preliminary
True $t\bar{t}$
Pseudo-data $t\bar{t}$
Unfolded $t\bar{t}$
10^2
10
0
200
400
600
800
1000
1200
1400
M_{tt} [GeV/c^2]

...$d\sigma/dM_{ttbar}$

- Backgrounds are estimated similar to the ttbar cross section measurement (saw in Andrea Costa's talk)
- Check consistency with SM using the Anderson-Darling statistic.





No discrepancies from the SM expectations is found

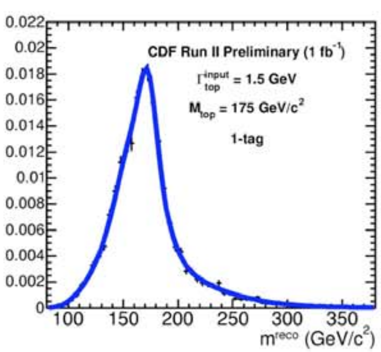
...$d\sigma/dM_{ttbar}$, Systematics

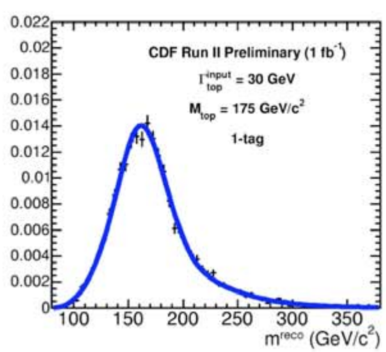
Summary of systematic uncertainties for $d\sigma/dM_{t\bar{t}}$ measurement
CDF II Preliminary, $\int \mathscr{L} = 1.9 \pm 0.1\ fb^{-1}$

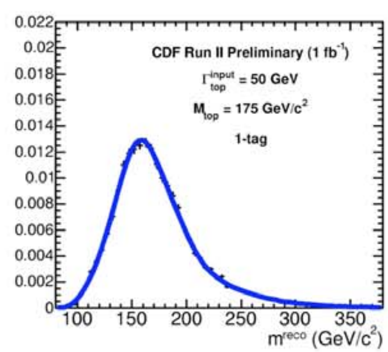
$M_{t\bar{t}}$ $[GeV/c^2]$	0-350	350-400	400-450	450-500	500-550	550-600	600-700	700-1400
MC Generator [%]	13.6	10.0	2.8	4.9	10.9	15.7	19.6	22.1
Inital State Radiation [%]	8.7	5.8	1.2	4.5	6.7	6.9	6.4	6.1
Final State Radiation [%]	4.6	3.1	0.7	2.1	2.9	3.0	3.7	4.7
Jet Energy Scale [%]	16.0	11.0	2.1	7.9	12.9	15.8	17.9	19.3
Background Shape [%]	30.2	24.6	14.1	7.8	6.8	9.0	12.1	14.3
Background Normalization [%]	9.4	7.7	4.6	2.9	3.0	4.0	5.3	6.1
Acceptance [%]	4.1	4.2	4.2	4.2	4.2	4.2	4.2	4.2
MC PDF Set [%]	7.9	6.3	3.0	1.6	6.9	12.6	17.5	20.6
Total [%]	40.2	31.4	16.1	14.1	21.4	28.7	35.5	40.0

Width of the Top Quark

- Direct measurement of the top lifetime is very difficult
  - from the Heisenberg uncertainty, $\tau=\hbar/\Gamma$
- Using the χ^2 kinematic fitter (saw in Nick van Remortel's talk), reconstruct the mass of top quark in each event
- Template method to find the width, using
  - A priori estimate for background composition
  - Background mass shapes from MC except for QCD
  - MC samples with discrete values of true Γ_t^{input}







Lepton+jet selection

- ✓ one high p_T *e* or *μ*
- ✓ missing E_T of at least 20 GeV
- ✓ ≥ 3 jets with $E_T \geq$ 15 GeV
- ✓ at least two b-tagged jet

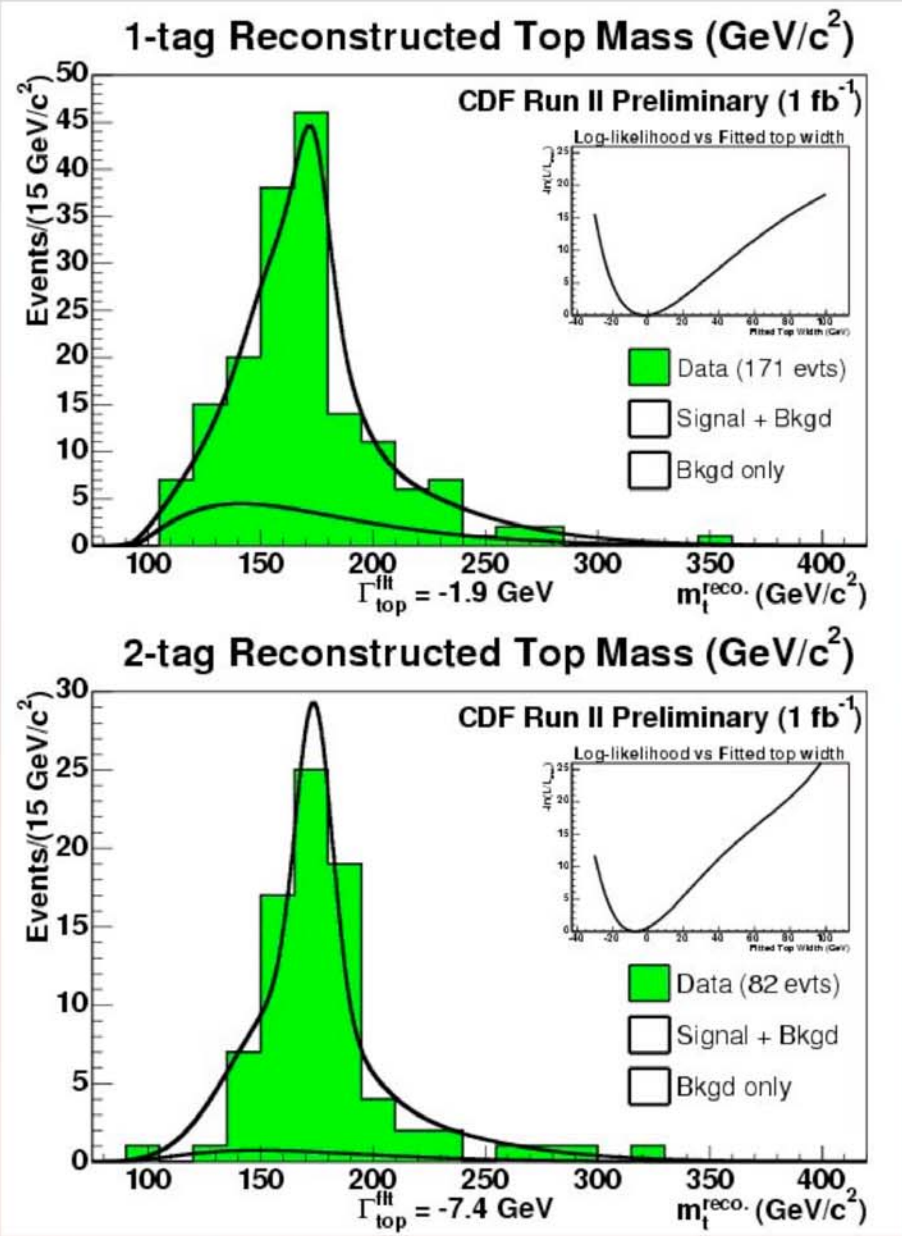
If 1-tag

- ✓ 4th jet with $E_T \geq$ 15 GeV

If 2-tag

- ✓ 4th jet with $E_T \geq$ 8 GeV

…Width of the Top Quark

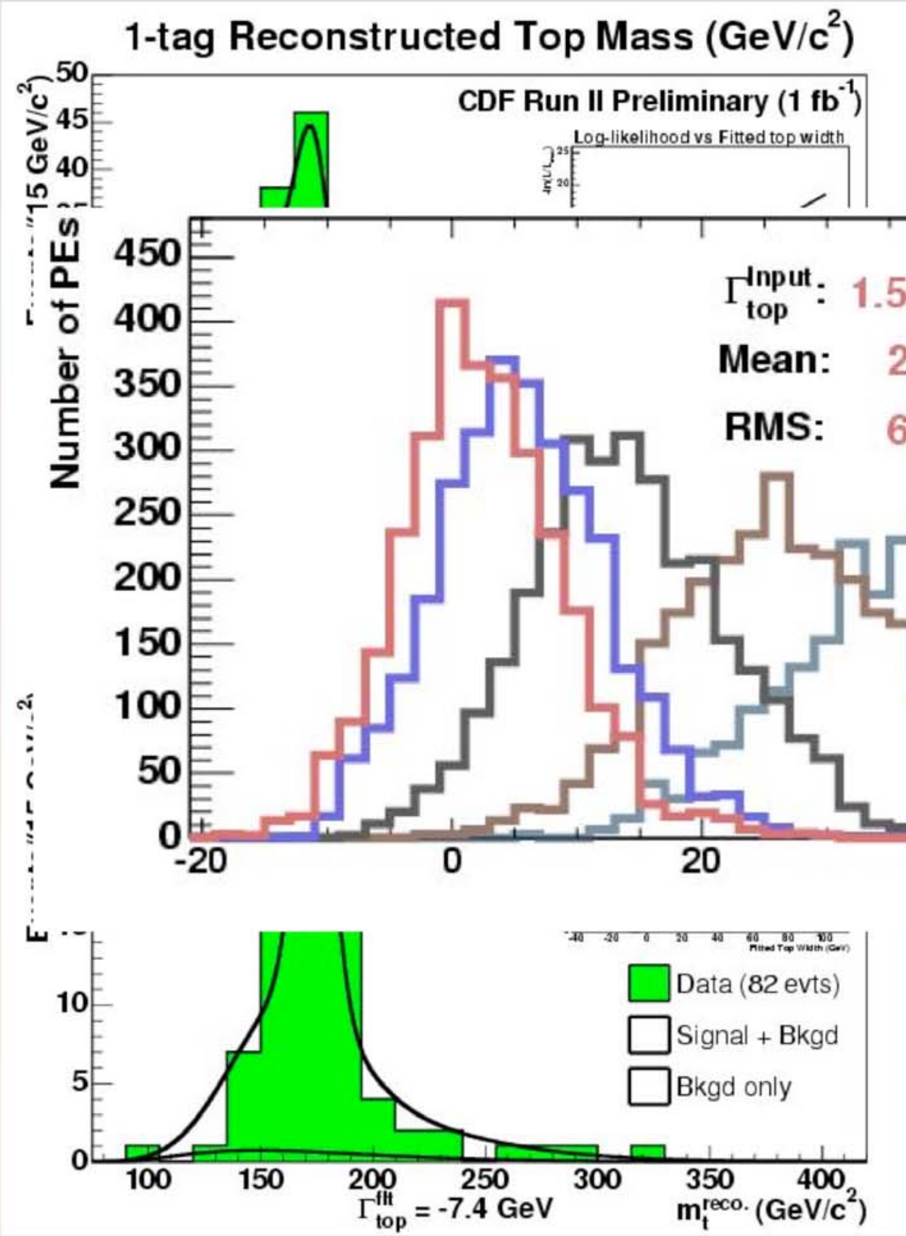


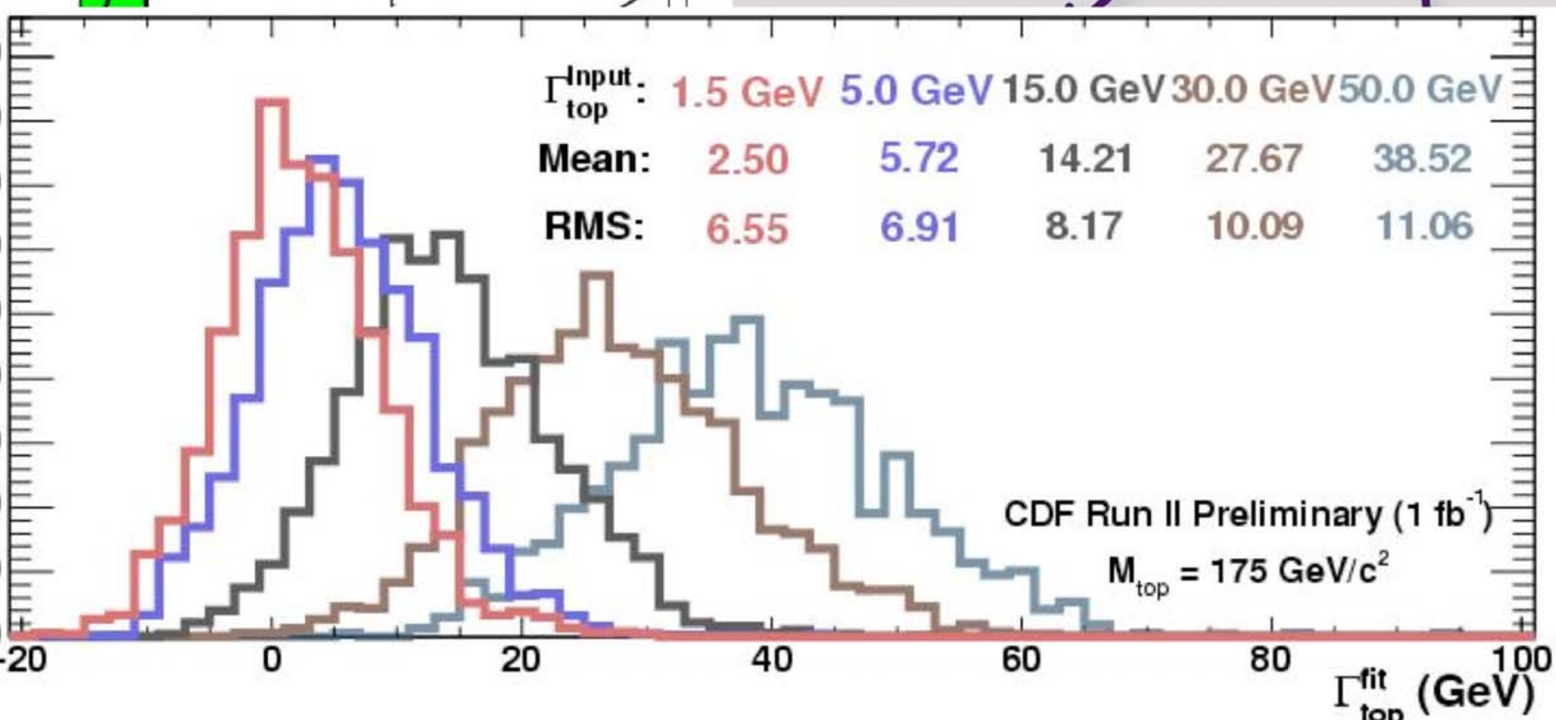
$$\mathcal{L} = \mathcal{L}_{shape} \times \mathcal{L}_{bg}$$

Joint probability density for a sample of N reconstructed mass with the expected background fraction

Keeps the number of bkg to its expected value within the uncertainties

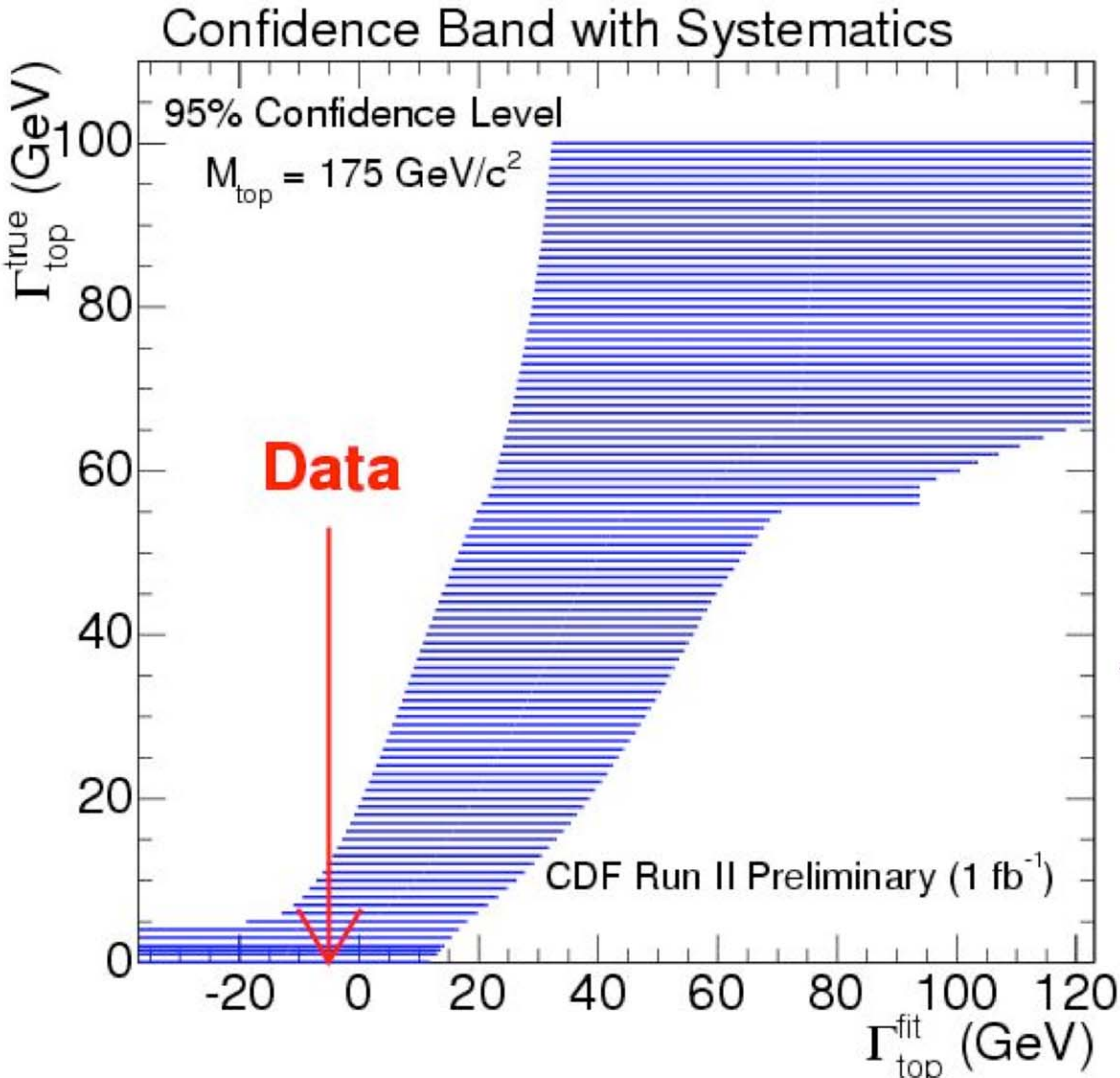
…Width of the Top Quark





$\mathcal{L}=\mathcal{L}_{shape}\times\mathcal{L}_{bg}$

…bkg to its expected value within the uncertainties



$\Gamma_t < 12.7$ GeV
@ 95% C.L.

$\tau_t > 5.2 \times 10^{-26}$
@ 95% C.L.

Charge of the Top Quark…

Motivation

- Is the top quark we observe really the SM top quark?
  - Charge of +4/3 → exotic quark

Method

- Main components:
  - Charge of W
  - Pairing the b quark with the W
    - Use top kinematic fitter in LJ
    - 2 highest E_T jets as b jets in DIL, M^2_{lb}
  - Charge of b quark

$$\text{JetQ} = \frac{\sum (\vec{p}_{track} \bullet \vec{p}_{jet})^x \cdot Q_{track}}{\sum (\vec{p}_{track} \bullet \vec{p}_{jet})^x}$$

- Separate events to the SM and XM sets

Lepton+jet selection (LJ)

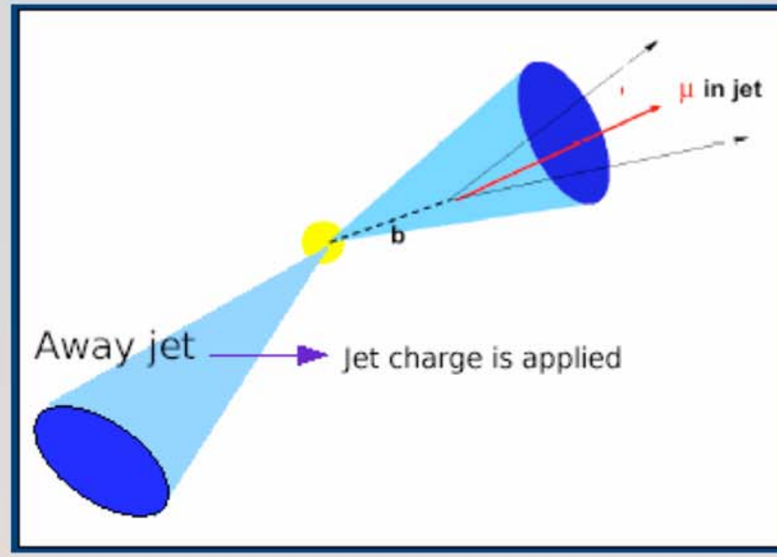
- ✓ one high p_T *e* or μ
- ✓ missing E_T of at least 20 GeV
- ✓ ≥ 3 jets with $E_T \geq 20$ GeV
- ✓ one jet with $E_T \geq 12$ GeV
- ✓ at least two b-tagged jet

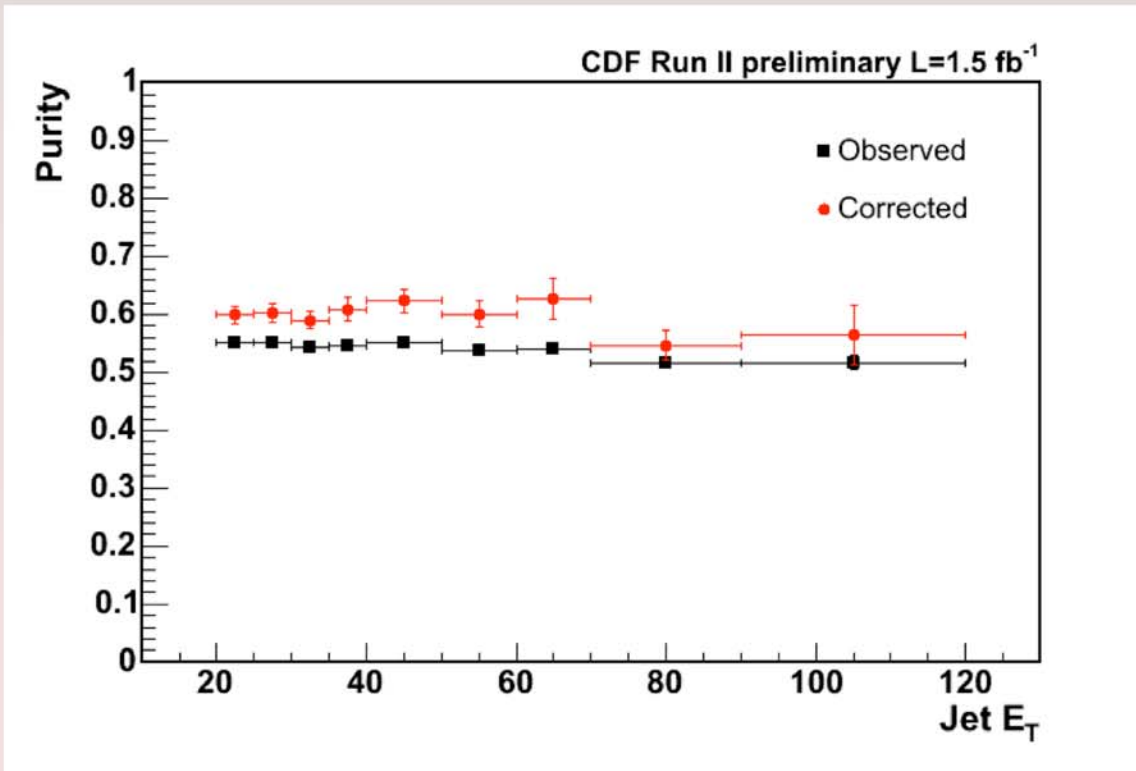
Dilepton selection (DIL)

- ✓ at least 2 high p_T *e* or μ *with unlike charge*
- ✓ missing E_T of at least 25 GeV
- ✓ ≥ 2 jets with $E_T \geq 15$ GeV
- ✓ $H_T > 200$ GeV
- ✓ at least one b-tagged jet

…Charge of the Top Quark…

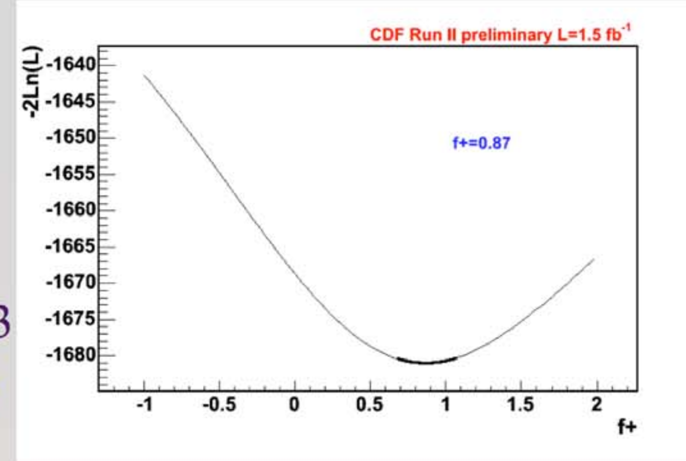
- Calibrating the jet charge algorithm with data
  - Using dijet data sample on selected b-bbar events where one of b's decay semileptonically to a muon



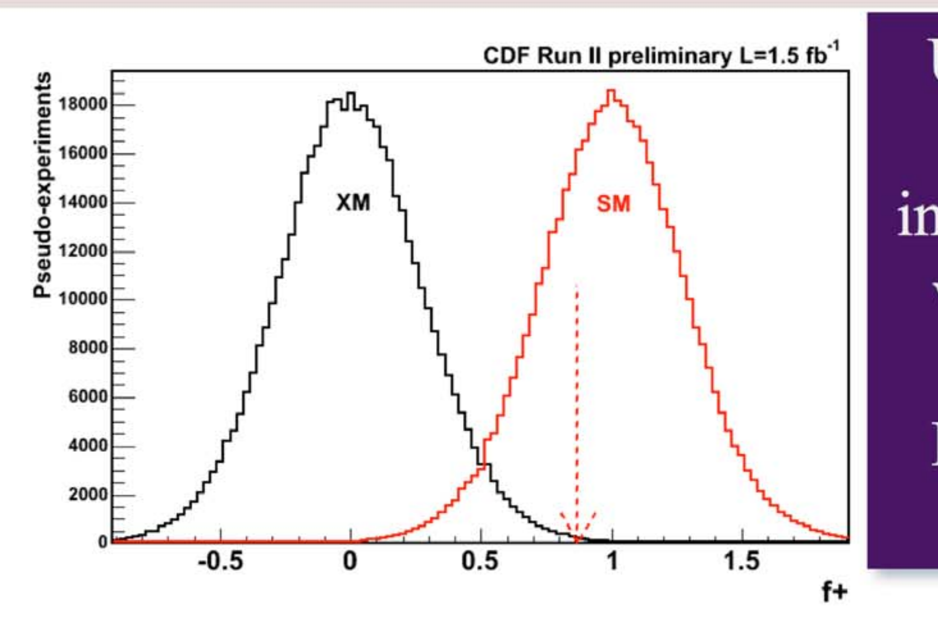


...Top Quark Charge

- Combining right pairing with the Jet charge information, we get
  - N+ = number of SM like events with top charge +2/3
  - N- = number of XM like events with top charge -4/3
- Distribution of the fraction of SM like pairs (f+) assuming either the Exotic or the Standard Model. Indicated is the measured f+ value of 0.87 which corresponds to a p-value of 0.31 .



the Log Likelihood curve for the observed N+ and N-



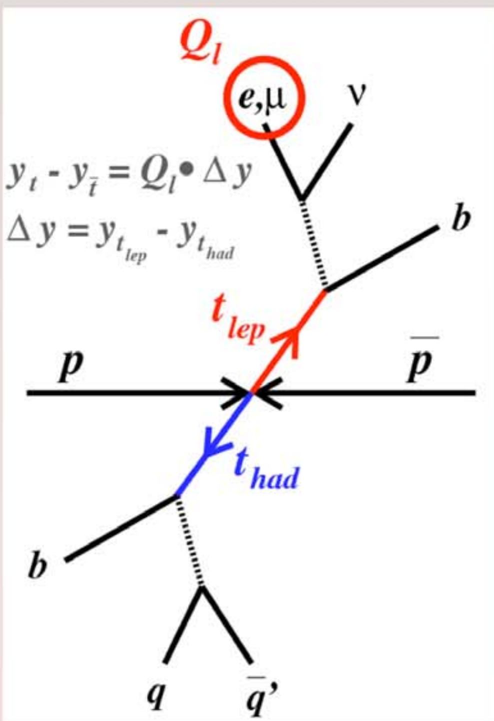
Using 1.5fb-1 of data (DIL and LJ) and defining the probability of incorrectly rejecting the SM to be 1%, we found the result to be consistent with the SM, while excluding the Exotic quark hypothesis (XM) with 87% confidence.

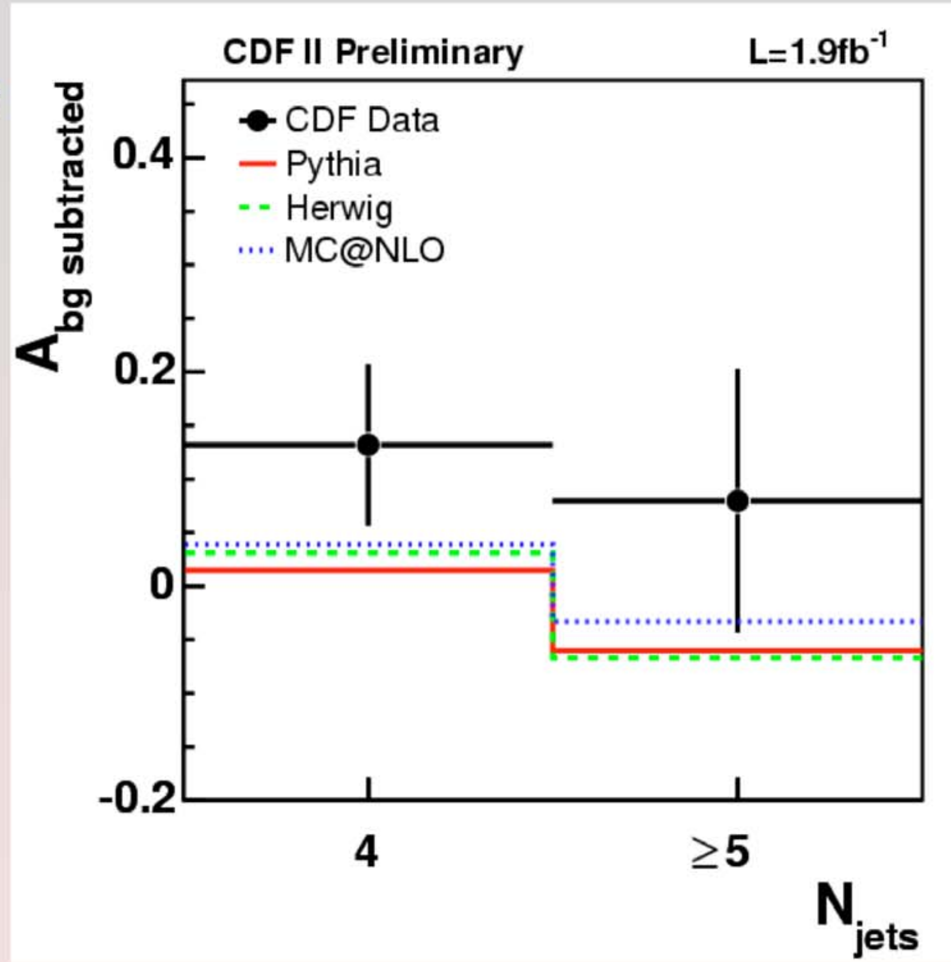
Charge Asymmetry in ttbar Production

- ***According to the SM,*** Afb = 0.04 +/- 0.01
- ***Two methods are used at CDF***
  - One takes advantage of the production angle of hadronically decaying top quark, defined as the angle between the top direction and the beamline in the laboratory rest frame.
  - Afb = $(N_f - N_b)/(N_f + N_b)$,
    - N_f (N_b) number of events in which the production angle is + (-)
  - We find a value of
    - Afb = 0.17 +/- (0.07)stat +/- (0.04)syst

Charge Asymmetry in ttbar Production

- The second analysis uses the rapidity difference between the semileptonically decaying and the hadronically decaying top quark multiplied with the charge of the charged lepton

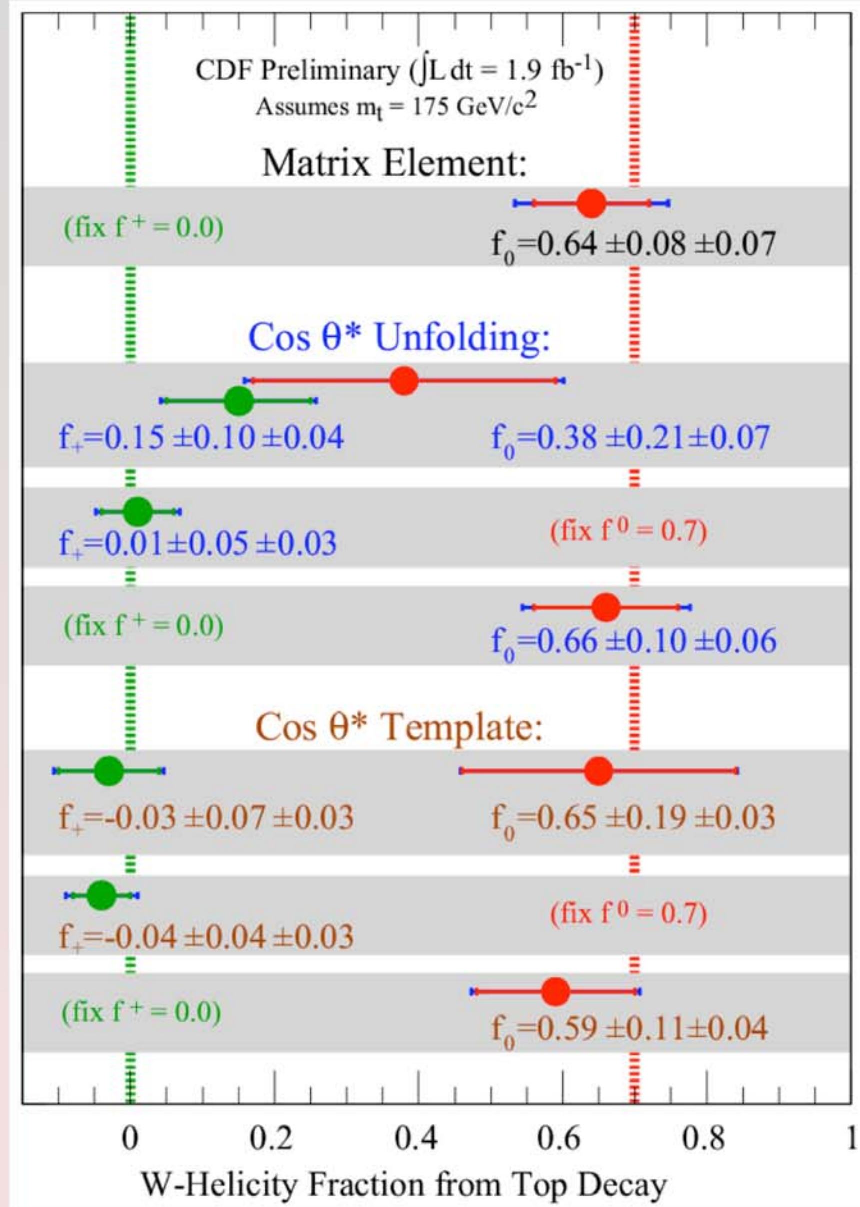




W Helicity Fraction from top Quark Decay

Motivation

- Decay products preserve the helicity content of the underlying weak interaction
- Chance to probe the V-A structure of the weak interaction in the top-quark decay
- Hint of new physics if helicity fractions differ from SM predictions



Summary

- There is a large interest in the study of top quark

- We are trying to tackle as many possibilities to learn more about the SM and the possible deviations and getting closer to finding new physics

- The result may be mostly statistically limited, but the search goes on so stay tuned…

Backup Slides

Combining gg fraction measurements

$$
\begin{aligned}
C_{f+sys}^{NN} &= C_f^{NN} + Gauss(0, \Delta_{uncorr}^{NN}) + G_{corr} * \Delta_{corr}^{NN} \\
C_{f+sys}^{TK} &= C_f^{TK} + Gauss(0, \Delta_{uncorr}^{TK}) + G_{corr} * \Delta_{corr}^{TK} \\
\text{where} & \\
G_{corr} &= Gauss(0,1)
\end{aligned}
$$

$$
\begin{aligned}
C_{f+sys}^{COM} &= w_{NN} * C_{f+sys}^{NN} + (1 - w_{NN}) * C_{f+sys}^{TK}, \\
\text{where} & \\
w_{NN} &= \frac{\frac{1}{\sigma_{NN}^2}}{\left(\frac{1}{\sigma_{NN}^2} + \frac{1}{\sigma_{TK}^2}\right)}, \\
\text{where} & \\
\sigma_{NN} &= \sqrt{(\sigma_{NN}^{stat})^2 + (\Delta_{uncorr}^{NN})^2 + (\Delta_{corr}^{NN})^2}.
\end{aligned}
$$

SVD

- To retrieve the true distribution of Mttbar, one can
  - Model the effects which distort Mttbar with MC
  - Produce a probability response matrix, ***A***, such that $Ax = b$ where x is the true distribution and b is the measured distribution
- Problem for bins that are not well-populated
  - Results in solutions with large difference from the true value
- Alternatively, one can use the SVD of a response matrix filled with actual numbers of events instead of probabilities, to regularize the solution

Estimating Gluon-Rich Fraction in Background

Sample	f_g - no tag	f_g - tagged
W+1 jet	0.41 ± 0.01	0.56 ± 0.05
W+2 jet	0.51 ± 0.02	0.42 ± 0.08
W+3 jet	0.56 ± 0.04	0.44 ± 0.12
Extrapolated W+≥4 jet, (f_g^{LF}) (f_g^{HF})	0.72 ± 0.05	0.27 ± 0.19
LF fraction in background (f_b^{LF})	-	0.55 ± 0.11
HF fraction in background (f_b^{HF})	-	0.45 ± 0.09

- We calculate f_g^{bkg} assuming Gaussian distributions for the variables used in the following equation using the above values

$$f_g^{bkg} = f_b^{LF} f_g^{LF} + f_b^{HF} f_g^{HF}$$

- We find $f_g^{bkg} = 0.54 \pm 0.09$

- HF background is anything that can have a real tag (Wc, Wcc, Wbb, Single Top and half of nonW) and the rest is what we consider LF